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THE SOURCES AND DISTRIBUTION OF MERCURY AND ARSENIC IN THE AFTON COPPER SMELTER, KAMLOOPS, BRITISH COLUMBIA

by

T.T. Chen* and P. Pint*

ABSTRACT

Based on the mineralogy, phase characteristics and compositions of the smelter feed, the smelter products and the smelter wastes, the sources and distributions of mercury and arsenic in the Afton copper smelter, Kamloops, British Columbia have been determined. Of the total mercury in the feed, approximately 33% is in solid solution in tennantite, 51% is in native copper and 16% occurs as mercurian silver. Arsenic in the feed occurs predominantly as tennantite, and extraction of tennantite prior to smelting would eliminate almost all the arsenic and approximately one-third of the total mercury. Under current smelting conditions, 99.6% of the total mercury in the feeds enters the off-gas cleaning system. From this off-gas, about 1% of the total mercury, occurring as dust, is recirculated to the flotation concentrate; 4.6% of the total mercury is discharged as scrubber sludge. Approximately 78% of the total arsenic in the smelter reports in the copper products; 20% is incorporated in the dust and slag which are subsequently recirculated to the mill. Only 1.8% is rejected as scrubber sludge, and less than 0.2% is released to the mercury scrubber.

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INTRODUCTION

The Canadian smelting industry is deeply concerned about the occurrence and distribution of potentially toxic elements such as mercury and arsenic in smelting circuits. In an effort to help the industry minimize any deleterious environmental effects of such elements, CANMET recently inaugurated a program to ascertain the mineralogy, phase characteristics and distribution of potentially toxic trace elements in Canadian non-ferrous metal extraction circuits (1). The ore processed at the recently opened Afton copper smelter at Kamloops, British Columbia contains small amounts of mercury and arsenic. The plant is notable in that it utilizes extensive scrubbing facilities to remove SO_2, Hg, As, etc. from the smelting off-gases prior to their discharge. The known existence of mercury and arsenic in the feed together with the presence of massive gas scrubbing facilities presented an opportunity to determine the form and distribution of these elements in both the processing and gas-treatment operations. The present report describes the results obtained on smelter samples taken in December, 1980 and February, 1981, and also discusses some techniques by which improvements could conceivably be effected in the containment of potentially toxic heavy elements.

DESCRIPTION OF THE AFTON OPERATION

The Afton copper mine, about 13 km west of Kamloops, B.C., is being developed as an open pit by Teck Corporation. Reserves are about 31 million tonnes of ore grading 1.0% copper at a 0.25% cutoff, and also containing recoverable gold (0.58 ppm) and silver (4.19 ppm). The mine is at the northwestern end of the Iron Mask batholith, and the ore occurs at the

junction of two major fault zones (2). The ore is unusual in that a substantial proportion of native copper occurs in the upper horizons. Native copper is commonly accompanied by chalcocite and cuprite. In the lower horizons, the ore is characterized by bornite and chalcopyrite and its average grade is fractionally higher than that of the upper horizons. The detailed geology of the deposit has been described by Carr & Reed (2), who reported that mercury occurs in small amounts in the Afton mine and that mercury-vapour anomalies are related to the subjacent faults coincident with Tertiary strata.

Approximately 68,000 tonnes/day of waste rock and ore are mined from the pit on a five-day week basis to provide 6,350 tonnes/day of ore to the concentrator (3). Because of the substantial amounts of coarse-grained native copper, the ore is processed through a gravity separation circuit, followed by a flotation circuit. The gravity circuit removes much of the coarse-grained native copper and recovers about 30% of the total copper as a metallic concentrate assaying more than 80% Cu. The flotation circuit recovers the fine-grained native copper and copper sulphide minerals as a flotation concentrate assaying more than 50% Cu and accounting for 57% of the total copper input. The flotation concentrate received in December 1980 contained 99 ppm Hg and 0.30% As; the metallic concentrate contained 106 ppm Hg and 0.03% As. The details of the milling process have been described (3).

The Afton smelter employs a Top Blown Rotary Converter (TBRC) to process its copper concentrates. Smelting and converting are done in a single 72-tonne capacity TBRC. A simplified flowsheet of the smelter operation is given in Fig. 1. The flotation concentrate (as slurry with 12% solids) from the mill is passed through a concentrate thickener, a disc filter and a rotary dryer. Dryer flue gas is cleaned in a baghouse, and the dust is recycled to

the concentrate thickener. The dryer discharge, averaging 7% moisture, is combined with the metallic concentrate in a ratio of approximately 3:1, then mixed with burnt lime and subsequently fed to the TBRC. Coke is added later in the processing cycle to reduce copper oxides. The flotation concentrate charged to the TBRC is variable in composition (Cu 30-74%, SiO_2 8-29%, S 2-19%, Fe 2-20%, H_2O 7%) whereas the metallic concentrate is rather uniform (approximately Cu 82%, SiO_2 3%, S 0.2%, Fe 8%, H_2O 4%).

The TBRC process is a batch smelting operation, each cycle comprising smelting and slag skimming, converting and reduction, and casting, produces approximately 40 tonnes of copper (99.15% Cu) and 32 tonnes of slag (Cu 4.3%, Fe 16%, SiO_2 33%, CaO 22%). The slag is subsequently recycled to the mill to recover more copper. In 1979, approximately 131 tonnes/day of concentrate (with an average grade of 61.4% Cu) were fed to the TBRC and produced about 80 tonnes/day of copper.

The process off-gas from the TBRC is vented through a gas cooler. The cooled gas (approximately 370°C) then passes through an electrostatic precipitator to remove the dust. The dust (approximately 1.5% of the TBRC feed) is contacted with lime slurry and is recirculated to the concentrate thickener. The gas from the precipitator is passed through a high pressure venturi scrubber, an alkaline SO_2 scrubber, and a cold water mercury scrubber. The sludge produced in the SO_2 scrubber is discarded in the tailings pond, and the elemental mercury removed by the cold water scrubbing system accumulates in the liquor holding tank. The process gas discharged from the mercury scrubber is reheated to 163°C is directed to the stack. The detailed smelting process has been described by Nickel et al. (4).

SAMPLES AND ANALYSES

Two sets of samples were studied. The first, taken at the Afton smelter on December 2, 1980, consists of flotation concentrate (dryer discharge), metallic concentrate, copper product, slag, electrostatic precipitator dust and SO_2 scrubber sludge (to tailings pond). The second set, sampled on February 16, 1981, consists of recycle-dust from the rotary dryer, recycle-dust/lime slurry from the electrostatic precipitator, and venturi scrubber underflow from the gas handling system. Sludge #1 and Sludge #2 are two different samples of the SO_2 scrubber sludge.

Wet samples from the smelter were obtained for this study. The samples were first dried at 70°C under nitrogen and then blended thoroughly to ensure homogeneity. The gases evolved during drying were passed through caustic scrubbers to collect any evolved mercury, which was determined at the end of the drying operation. The S, Cu, Pb, As, Fe, Ag, Zn and Sb contents were analyzed at CANMET whereas mercury concentrations were determined by a commercial assay laboratory. Native copper was separated by heavy liquid, magnetic separator and hand-picking from the metallic concentrate for analysis. The analytical results are given in Tables 1 and 2. In Table 1, the total mercury concentrations (i.e., the mercury in the dried solids plus that in the caustic scrubber) and the mercury content of the dried solids alone are reported for each sample.

Polished sections of these samples were prepared, and the various phases in each section were identified using a reflected light microscope, an electron microprobe, and energy-dispersive analyzer, a scanning electron microscope (SEM) and a Debye-Scherrer X-ray camera. The compositions of the phases were determined using the electron-microprobe (1). Mercury carriers were identified using wavelength-dispersive X-ray spectrometry and

X-ray energy-dispersive analyzer (EDX) on the electron microprobe, and an X-ray map and EDX on the SEM. The results of these investigations are discussed below.

MINERALOGY AND PHASE CHARACTERISTICS

Flotation concentrate (dryer discharge)

The flotation concentrate (dryer discharge) contains copper from the mill that is produced from raw ore as well as from recirculated slag, together with recycled dusts from the TBRC electrostatic precipitator and the rotary dryer itself (Fig. 1).

In the dryer discharge, native copper, chalcocite and gangue minerals occur in major quantities (Fig. 2); chalcopyrite, bornite, pyrite, tennantite and cuprite occur in minor amounts, whereas magnetite, hematite and delafossite occur in trace amounts. Native gold, auricupride, mercurian silver and cobaltite, [(Co,Ni)AsS] associated with tennantite-bornite-chalcopyrite, are rare. The major gangue minerals are albite, K-feldspar, quartz and possibly nepheline? (a Na-K-Al-silicate); minor amounts of fluorite, calcite, apatite, pyroxene, amphibole, epidote and biotite also occur.

Native copper is usually present as free flakes, but a minor amount occurs associated with chalcocite or silicates. The native copper usually contains trace amounts of Hg (0-0.34%). Typical analyses of the copper are given in Table 3. Chalcocite, chalcopyrite and bornite usually occur as free grains; minor amounts occur as composite grains with each other, or with pyrite, tennantite and native copper. The minerals generally do not contain As, Hg or Ag; their compositions are given in Table 4. Some of the chalcopyrite contains extremely fine-grained bornite exsolution lamellae

(Fig. 3) and this material is tarnished rapidly. The compositions of the tarnished chalcopyrite deviate slightly from the ideal formula (Table 4). It is not known whether these lamellae are original or if they are a roaster-generated texture since some of the dust from the smelter is recirculated to the flotation concentrate thickener.

Native gold was found as inclusions (1-2 μm size) in chalcopyrite, and as intergrowths with auricupride (Fig. 4) or with native copper. Native gold usually contains minor amounts of Cu (2.2 - 3.2 wt%) and Ag (6.9 - 7.5 wt%), whereas auricupride contains trace amounts of Ag (0.2 - 0.5 wt%) (Table 5). Neither Zn nor Hg was detected in either mineral. Mercurian silver (amalgam) occurs as intergrowths and as inclusions in native copper and chalcocite; the compositions are given in Table 6. Mercurian silver usually contains minor amounts of Cu; the highest Cu content observed is 8.2 wt%. The mercury contents observed vary from 0.3 to 17.4 wt%, with an average of 8.19 wt%. No Sb was detected in these samples.

Cuprite usually occurs as free grains, whereas delafossite commonly occurs as veinlets intersecting cuprite grains. The compositions of these minerals are given in Table 7. Cuprite generally contains a small amount of FeO (1 - 4 wt%), whereas delafossite contains minor amounts of TiO_2 (1.6 wt%). Pyrite usually occurs as free grains although a minor amount is found as composite grains with chalcopyrite, chalcocite, tennantite and gangue minerals. The pyrite is usually free from inclusions, and generally contains minor amounts of Cu and As (Table 8). Copper contents vary from 0.6 to 2.4 wt%, whereas the As concentrations vary from 0.0 to 4.3 wt%. Mercury was not detected in the pyrite. The average composition of pyrite is (wt%): Fe 45.16, Cu 1.40, As 0.36, S 52.60, total 99.52, corresponding to $Fe_{0.973}\ Cu_{0.027}\ As_{0.006}\ S_{1.977}$.

Tennantite usually occurs as free grains although minor amounts are present as composite grains with chalcopyrite, chalcocite, bornite, silicate minerals and pyrite. The compositions of some tennantites are given in Table 9. The average composition is (in wt%): Cu 44.46, Fe 3.32, Zn 3.11, Hg 0.23, As 16.67, Sb 4.72 and S 28.02, total 100.53, corresponding to $(Cu_{10.42}\ Fe_{0.88}\ Zn_{0.71}\ Hg_{0.02})_{\Sigma 12.03}\ (As_{3.31}\ Sb_{0.58})_{\Sigma 3.89}\ S_{13}$. Arsenic contents vary from 7.5 to 19.8 wt%, whereas Hg contents are as high as 1.8 wt% (minimum detection limit 0.10 wt% Hg). The highest Hg analysis (Anal. 10) corresponds to $(Cu_{10.31}\ Fe_{0.59}\ Zn_{0.96}\ Hg_{0.14})_{\Sigma 12.00}\ (As_{3.64}\ Sb_{0.25})_{\Sigma 3.88}\ S_{13}$.

Dust particles of burnt lime, as white subspherical aggregates (Fig. 5), also occur in the dryer discharge. The aggregates consist mainly of $CaCO_3$ and $Mg(OH)_2$ although $Ca(OH)_2$ is also present in some of the aggregates. Chemical analyses of these aggregates indicated major amounts of CaO and MgO as well as minor and variable amounts of SiO_2 (Table 10). Fine particles of coke were also found in the dryer discharge. X-ray energy-dispersive analysis on some of these particles indicated only a trace amount of Si or S; X-ray powder diffraction analysis showed the presence of a major amorphous phase together with trace amounts of quartz and other unidentified phases. Crushed slag and electrostatic precipitator dust are also found in trace amounts in the dryer discharge. Metallic iron, possibly from the grinding medium, is also present in trace amounts.

Metallic concentrate

The metallic concentrate consists mainly of native copper and a major amount of hematite-magnetite and gangue minerals, a minor quantity of

metallic iron (contamination?) and trace amounts of pyrite, chalcocite, bornite, chalcopyrite, tennantite, cuprite, mercurian silver, delafossite and goethite (Fig. 6).

Native copper usually occurs as free flakes although intergrowths with mercurian silver were also observed (Fig. 7). A few grains have a cuprite rim or, less frequently, a goethite rim. Some native copper contains inclusions of quartz, cuprite, Cu-silicate and mercurian silver; others have extensively oxidized to cuprite. The native copper usually contains trace concentrations of Hg, with values as high as 0.34 wt% (Table 3) having been determined. Arsenic is generally not detected (<0.06%) in the native copper; however, in some grains, the As content reaches 4.1 wt%. The As-bearing native copper appears whiter ("bleached") than the normal native copper under the reflected-light microscope. Mercurian silver (amalgam) usually contains minor quantities of Cu. Some of the compositions are given in Table 6. Hematite and magnetite usually occur as mutual intergrowths; the bulk composition contains Fe 70.3%, Ti 0.1% and O 29,6% (by difference); other elements were not detected. The gangue minerals observed are mainly K-feldspar, quartz, albite, dolomite, and a (Na,K,Al)-silicate (possibly nepheline). Minor quantities of metallic iron, occurring as isolated grains, were also found in the metallic copper concentrate. Some grains have alteration rims (goethite) and appear to be attached to native copper and silicates.

In general, the mineralogy of the metallic concentrate is similar to that of the flotation concentrate except that the metallic concentrate has

a larger amount, and a coarser size, of native copper and hematite-magnetite, but contains no recycled smelter dust. The amount of slag in the metallic concentrate is extremely low.

Recycle dust from dryer

Recycle dust from the dryer is mineralogically similar to the flotation concentrate. The dust consists of major native copper, chalcocite, gangue minerals, minor chalcopyrite, bornite, magnetite-hematite, cuprite, slag, and trace amounts of pyrite, tennantite, mercurian silver, coke, burnt lime and electrostatic precipitator dust (Fig. 8).

The copper product

The copper product studied contains numerous (approximately 15% by area) fine grained (1-10 μm) inclusions of Cu_2O and a minor amount of a $Cu_{13}Sb_2As_5O_{17}$ phase (Fig. 9). Isolated grains of Cu_2O and SiO_2 rarely occur in the sample. The Cu_2O is usually present as light spherical inclusions in metallic copper, whereas $Cu_{13}Sb_2As_5O_{17}$ is present as long grey stringers (Fig. 10). The chemical compositions of the metallic copper and the $Cu_{13}Sb_2As_5O_{17}$ phase are given in Tables 11 and 12, respectively. The metallic copper contains approximately 0.035 wt% Ag and 0.265 wt% As; some grains were noted to have as much as 0.81 wt% As as well as minor Sb and Hg.

Slag

Fine-grained (from 3 to 500 μm), angular-shaped slag particles were studied. The slag consists mainly of Fe-Ca silicates, Fe oxides and also glass, with metallic copper disseminated in the silicate and glass matrices (Fig. 11). The silicates are mainly pyroxene whereas the oxides

are spinel-type. The former usually occurs as very fine-grained dendrites and skeletal or needle-like crystals, whereas the latter is usually present as coarse-grained short euhedral crystals in the silicate matrix (Fig. 12). The silicates identified are: (elements in brackets are of minor importance and are present in variable quantities) Fe-Ca-(Mg,Al,K) silicate, Fe-(Mg) silicate, Ca-Fe-(Al,Mg,K,Cu) silicate, and Ca-Fe-Al-(Mg,K) silicate. The oxides identified are: Fe-Cr-(Al,Mg,Cu) oxide, Cu-(Fe) oxide, Fe-Cr oxide, Fe-Cr-Al oxide and Fe oxide. The glass is mainly $CaO-FeO-SiO_2-(Al_2O_3,MgO,K_2O)$ and constitutes the matrix. Metallic copper, occurring as 1-10 μm diameter sized spherules disseminated in the silicate matrix, usually contains trace amounts of Fe and is responsible for essentially all the Cu content of the slag.

Electrostatic precipitator dust

Ninety-five percent of the electrostatic precipitator dust consists of 5-150μm diameter sized spherules (i.e., solidified droplets or condensed fumes) of metallic copper, copper oxides, glass and copper and calcium sulphates (Fig. 13). The remaining 5% consists of angular grains of K-feldspar, quartz, K-Na-Al silicate, pyrite, chalcopyrite, bornite and hematite and irregular grains of sulphates, arsenates and glass.

The spherules are generally heterogeneous in composition (Fig. 14), possibly due to rapid solidification from the vapour or liquid states. The metallic copper spherules are usually uniform in composition although some contain trace amounts of Fe, Ca, or less frequently, K, Si or S. The metallic copper spherules usually have a rim of, or are enclosed by spherules of Cu_2O, $(Ca,Cu)SO_4$ (Fig. 13), or by spherules of $CaO-Al_2O_3-CuO-SiO_2$, $CuO-Al_2O_3-(K_2O,CaO,FeO)-SiO_2-SO_4^{=}$, and $CaO-MgO-(Al_2O_3)-SiO_2-SO_4^{=}$ glass.** Components

in parentheses are of minor importance and are present in variable amounts. Some metallic copper spherules also contain small Cu_2O dendrites or spherules. Copper oxide spherules consist of Cu_2O-CuO intergrowths (Fig. 15). The Cu_2O usually occurs as the major phase and the CuO is present in variable amounts as the minor phase. The spherules usually have a rim of $CuSO_4$ or $CuSO_4.5H_2O$ (Fig. 16); some are rimmed by $(Ca,Cu)SO_4$, $Cu(Ca)SO_4$, Cu-K-$SO_4^=$-H_2O, or glass** of CaO-SiO_2-As_2O_5-(CuO,Al_2O_3,K_2O,$SO_4^=$) and CaO-Al_2O_3-SiO_2-As_2O_5-CuO-$SO_4^=$ (Fig. 17). Some of these spherules also contain metallic copper inclusions. Other oxide spherules observed are Cu-Fe oxide and Cu-(Fe,Ca) oxide; these are possibly spinels as indicated by X-ray diffraction analysis. Trace amounts of α-FeO(OH) were also identified in the sample. Copper sulphate spherules (Fig. 17) are usually variable in composition, and contain small amounts of K, Fe, Ca, or As. Although only $CuSO_4$ and $CuSO_4.5H_2O$ were confirmed by X-ray diffraction analysis, other hydrated or hydrous Cu-, or (Cu,K,Ca) sulphates probably also occur. The detection of the sulphates is rendered difficult by the hygroscopic nature of the dusts. $CaSO_4$ spherules are uniform in composition although some contain a minor amount of Cu, K, or As (Table 13). Some $CaSO_4$ spherules are also present as aggregates of needle-like crystals.

All the "silicate" spherules (Figs. 13, 14) appear to be non-crystalline, since X-ray diffraction analyses did not show any crystalline characteristics. The "silicate" spherules are thus considered to be glass whose composition is variable from spherule to spherule and within individual spherules. The components**, however, are mainly CuO, CaO, Al_2O_3, FeO or Fe_2O_3, SiO_2, with secondary K_2O, MgO, Na_2O and TiO_2. Some spherules also include a small amount of sulphate. The major compositional types of spherule observed are: CuO-Al_2O_3-CaO-FeO-K_2O-SiO_2, CuO-CaO-FeO-MgO-K_2O-Al_2O_3-SiO_2, CuO-

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** In this report, the component of Cu in glass is arbitrarily assigned as CuO, and As as As_2O_5.

Al_2O_3-K_2O-MgO-SiO_2-FeO, CuO-K_2O-FeO-SiO_2, Al_2O_3-CaO-FeO-K_2O-SiO_2, Al_2O_3-K_2O-CaO-FeO-SiO_2-Na_2O, CaO-FeO-MgO-Na_2O-SiO_2, CuO-FeO-CaO-K_2O-SiO_2, CuO-Al_2O_3-CaO-K_2O-Na_2O-SiO_2, CuO-Al_2O_3-K_2O-SiO_2, CuO-Al_2O_3-CaO-FeO-MgO-TiO_2-SiO_2, Al_2O_3-CaO-MgO-SiO_2-$SO_4^=$ and CuO-Al_2O_3-CaO-FeO-SiO_2-$SO_4^=$. Some spherules are partly enclosed by other spherules; for example, a CuO-FeO-SiO_2 spherule within a CuO-FeO-Al_2O_3-CaO-K_2O-SiO_2 spherule, and a CuO-MgO-CaO-FeO-K_2O-SiO_2 spherule in CuO-FeO-Al_2O_3-CaO-K_2O-SiO_2.

None of the spherules contain detectable mercury; however, a few have a substantial amount of arsenic. These are copper oxide spherules (0-5.3% As_2O_5, av. 0.72%), $CaSO_4$ and $(Ca,Cu)SO_4$ spherules (1.0% As_2O_5), Cu_2O-As_2O_5 spherules (8.2% As_2O_5), As_2O_5-$SO_4^=$ irregular grains (82.8% As_2O_5), Cu_2O-As_2O_5-$SO_4^=$ spherules (5.6% As_2O_5), and glass spherules of CuO-As_2O_5-K_2O-CaO-SiO_2-$SO_4^=$ (41% As_2O_5), CaO-FeO-SiO_2-As_2O_5-(CuO, Al_2O_3), and CaO-Al_2O_3-SiO_2-As_2O_5-(K_2O, CuO, $SO_4^=$), (Table 13, Fig. 18). Among these spherules, copper oxides, Cu_2O-As_2O_5 and Cu_2O-As_2O_5-$SO_4^=$ are most common. Some of these arsenic-carriers occur as rims of, or as irregular masses associated with, other spherules such as Cu_2O-CuO, $CuSO_4$, $CuSO_4.5H_2O$.

Electrostatic precipitator dust is highly oxidized and extremely hygroscopic; hydration takes place as soon as the dust is exposed to moisture. Although sulphur is present as sulphate in the solids, it is likely evolved as SO_3 gas from the TBRC; arsenic likely occurs as AsO_4^{3-} or AsO_3^- in the solids, but is probably evolved from the reactor as As_2O_3 or As_2O_5. Some of the $CuSO_4$ rims or spherules changed to a powdery $CuSO_4.5H_2O$ after two to three weeks of exposure to air. Because of the inhomogeneity of the spherules and the fact that the microprobe cannot detect water, it is not certain whether the arsenates or most of the other sulphate spherules also contain H_2O.

Recycle ESP dust-lime slurry

Dried solids of dust-lime slurry contain the same type of particles as the electrostatic precipitator dust (Fig. 19), plus a major amount of very fine-grained (less than 10 μm) Ca-Cu sulphate with trace amounts of phosphate, $CaSO_4.nH_2O$ (with trace amounts of Cu and P), and $Ca(OH)_2$ (Fig. 20). The major chemical constituents observed are CaO, Cu, CuO, $SO_4^{=}$, SiO_2, Al_2O_3, and minor amounts of FeO, As_2O_5, P_2O_5 and Cl. The mercury content of the solids was relatively high (Table 1); however, no compound containing probe detectable amounts of mercury has been found, and it must be assumed that the mercury is uniformly distributed throught the dust particles.

Sludge

Sludge samples (#1 and #2) were analyzed by X-ray diffraction methods because of their extremely fine grain-size. The sludge leaving the SO_2 scrubber was probably a mixture of $CaSO_3.\frac{1}{2}H_2O$ and $CaSO_4.\frac{1}{2}H_2O$; the material studied had been entirely oxidized to $CaSO_4.\frac{1}{2}H_2O$.

SOURCES AND DISTRIBUTION OF MERCURY AT THE AFTON SMELTER

The relative contributions of the various minerals to the total mercury input to the TBRC were determined in the following way:

1. The total mercury contribution by each of the flotation concentrate, metallic concentrate and recycle dust from the dryer was determined from the analyzed compositions shown in Table 1 and the know weights of each product

2. The quantity of mercury contributed by each mineral was based on chemical and microscopic analyses which showed that,

(i) native copper contained 115 ppm Hg; flotation concentrate,

metallic concentrate and dryer dust were comprised of 36 wt%, 76 wt% and 23 wt% native copper,

(ii) mercurian silver contained 8.1 wt% Hg; all of the silver in the feeds is as mercurian silver; the total amount of Ag carried by native gold and auricupride is negligible.

(iii) tennantite contained 0.23 wt% Hg; all of the Zn, Sb and the bulk of As are as tennanite.

3. The weight proportions of flotation concentrate, metallic concentrate and ESP recycle dust fed to the TBRC are 78%, 21% and 1%. The dust from the dryer is treated as part of the internal recycle.

Based on these data it was established that of the 99 ppm total mercury in the flotation concentrate, approximately 42% is contributed by tennantite, 16% by mercurian silver and 42% by native copper.

In the metallic concentrate (106 ppm Hg), approximately 5% of the mercury is carried by tennantite, 13% by mercurian silver and 82% by native copper. In the recycle dust from the dryer (67 ppm Hg), approximately 46% of the mercury is accounted for by tennantite, 21% by mercurian silver and 33% by native copper. When all the feeds to the Afton TBRC are taken into account, 33% of the Hg is carried by tennantite, 16% by mercurian silver, and 51% by native copper. For economic reasons, it may not be possible to reject mercury from the smelter feed, but theoretically a one-third reduction would be possible if the trace amounts of tennantite could be selectively removed. The copper rejected would amount to 270,000 kg/y along with the 1400 kg/y Hg.

The copper product contains 0.4 ppm Hg and accounts for only 0.2% of the total mercury in the circuit. The mercury is present as a solid solution in some of the metallic copper grains (Table 11). Slag contains 0.3 ppm Hg. No mercury-carrier has been identified in the slag.

Electrostatic precipitator dust assays 69 ppm of mercury. None of the phases identified in the dust contains probe-detectable amounts (detection limit 900 ppm) of mercury. The mercury probably occurs in solid solution or as a surface-adsorbed layer on the dust.

Dried solids of the recycle dust-lime slurry contain 158 ppm Hg. No mercury-bearing compound has been found in the recycle dust-lime slurry. The dried lime slurry dust consists of the same compounds as the electrostatic precipitator dust plus a major amount of very fine-grained Ca-Cu sulphate/phosphate, $CaSO_4.nH_2O$, and $Ca(OH)_2$. The mercury carriers in these two samples are likely the same. The much higher mercury concentration of the dried lime slurry collected on February 16, 1981 (158 ppm Hg) relative to the ESP dust collected on December 2, 1980 (69 ppm Hg) implies that major mercury variations occur in the processing circuit as a function of time.

The SO_2 scrubber sludge contains 107 ppm Hg. The sludge studied is mainly $CaSO_4.\frac{1}{2}H_2O$, but was probably $CaSO_3.\frac{1}{2}H_2O$ when it was precipitated in the SO_2 scrubber. Table 1 shows that approximately 5-6% of the mercury in the sludge is driven off during drying at 70°C, indicating that at least some of the mercury is present as easily volatilized compounds, such as, surface adsorbed mercury, elemental mercury, etc. From the above data, it is concluded that a major portion of the mercury in the smelter dusts is associated with the very fine-grained $CaSO_4.\frac{1}{2}H_2O$.

Employing the chemical analysis results and the weights of the various streams provided by the company, the distribution of mercury was determined in the processing circuit. The results are given in Table 14 and in Figure 21.

Of the total 4229 kg/y of mercury in the feeds to the TBRC, 78% is contained in the flotation concentrate streams and 22% in the metallic concentrate stream. The flotation concentrate stream consists of the sulphide metal concentrate and values from the recycled slag, the recycled lime-dust slurry from the dryer off-gas system and the lime slurry from the electrostatic precipitator. The metallic concentrate could contain metallics from the recycled slag.

During smelting when the temperature in the TBRC approaches 1300°C, 99.6% of the mercury entering the converter is released to the off-gas. Only 0.2% is retained in each of the slag and copper product. The SO_2 scrubber removes 4.6% of the mercury in the circuit with the remaining 94% entering the mercury scrubber.

SOURCES AND DISTRIBUTION OF ARSENIC AT THE AFTON SMELTER

In the flotation concentrate, metallic concentrate and recycle dust from the dryer, arsenic occurs mainly as tennantite (containing 16.71% As). Pyrite (0.36% As), cobaltite (44% As), arsenian copper (0.4-4.1% As) and recycle slag (0.08% As) also contain arsenic, but they contribute a negligible amount to the total arsenic input. The electrostatic precipitator dust (As concentration 0.59%) recycles 4% of the total arsenic from the TBRC to the flotation concentrate. The relative contributions of the various minerals to the total arsenic input was calculated in the same manner as used for mercury bearing minerals; i.e., from microscopic and chemical analyses.

Flotation concentrate contains 0.30% As. Approximately 4% of this amount is carried by electrostatic precipitator dust; 96% is carried by tennantite. Pyrite, cobaltite and arsenian copper contribute negligible

amounts of As to the concentrate. Metallic concentrate contains 0.03% As, and essentially all this arsenic is carried by the trace amounts of tennantite in the metallic concentrate. In the recycle dust from the dryer (containing 0.33% As) approximately 91% of the arsenic is carried by tennantite; the remainder is attributable to the electrostatic precipitator dust and pyrite. In summary, of the total arsenic entering the TBRC, 96% is carried by tennantite and 4% by recycle electrostatic precipitator dust. Selective removal of tennantite from the feed would largely resolve any environmental problems associated with arsenic emissions.

The average arsenic content of the copper product is 0.33% and this accounts for approximately 78% of the total arsenic from the TBRC. The arsenic occurs mostly as a solid solution in the metallic copper product (0.27% As) and also, in minor amounts, as $Cu_{13}As_5Sb_2O_{17}$ (21.8% As) which is present as inclusions in metallic copper. It is estimated that approximately 59% of the total arsenic in the copper product occurs in solid solution, and the remainder is attributed to $Cu_{13}As_5Sb_2O_{17}$.*

The slag contains 0.08% As and accounts for approximately 16% of the total arsenic in the TBRC. The nature of the arsenic in the slag has not been established.

Electrostatic precipitator dust contains 0.59% As and accounts for approximately 4% of the total arsenic released from the TBRC. Arsenic is

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* Copper product consists of metallic copper, $Cu_{13}As_5Sb_2O_{17}$ and Cu_2O; the difference between the total metal content in Table 2 and 100 wt% is attributed to oxygen. From the copper and oxygen contents, it is calculated that 72.7% Cu is carried by metallic copper and 23.4% Cu by Cu_2O and $Cu_{13}As_5Sb_2O_{17}$.

found in spherules of: copper oxides, $CaSO_4$, $(Ca,Cu)SO_4$, $Cu_2O-As_2O_5$, $As_2O_5-SO_4^{=}$, $Cu_2O-As_2O_5-SO_4^{=}$ and glass spherules of $CuO-As_2O_5-K_2O-CaO-SiO_2-SO_4^{=}$, $CaO-FeO-SiO_2-As_2O_5-(CuO-Al_2O_3)$ and $CaO-Al_2O_3-SiO_2-As_2O_5-(K_2O-CuO-SO_4^{=})$. Among these spherules, copper oxides, $Cu_2O-As_2O_5$, and $Cu_2O-As_2O_5-SO_4^{=}$ are most common.

Dried solids of the recycle dust-lime slurry contain 1.61% As. The constituents of the dried slurry dust are the same as those of the electrostatic precipitator dust; consequently, the As-carriers are expected to be the same.

The SO_2 scrubber sludge contains 0.1% As, and accounts for 1.8% of the total arsenic released from the TBRC. The nature of the arsenic in the sludge has not been established.

Employing the chemical analysis results from Table 2 and the weights of the various process streams provided by the company the distribution of arsenic has been determined as shown in Figure 22 and Table 15. Of the total 102,275 kg/y of arsenic entering the TBRC, 3% is contained in the metallic concentrate, 4% by recirculated electrostatic precipitator dust, and 93% by the flotation concentrate slurry from the ore dressing mill. The flotation concentrate (dryer discharge) studied accounted for 97% of the total As. However, as noted previously, the flotation concentrate stream (dryer discharge) consists of the sulphide-metal concentrate and values from the recycled dryer off-gas dust, the electrostatic precipitator dust of the TBRC and the recycled slag. After smelting, approximately 16% of the total As is incorporated in the slag which is subsequently recycled to the mill; 78% of the total As is retained in the copper product, and the remaining 6% is released to the off-gas. The off-gas is passed through an electrostatic precipitator where approximately 4% of the total As is removed in the dust. The remaining 2% is carried by the

off-gas into the venturi and SO_2 scrubbers where most of the remaining arsenic is removed. The sludge discharged from the SO_2 scrubber carries approximately 1.8% of the total As; the remaining 0.2% enters the mercury scrubber.

CONCLUSIONS

Based on studies of the smelter feed, smelter products and smelter wastes collected at the Afton smelter on December 2, 1980 and February 16, 1981, the following conclusions concerning impurity deductions are presented. Approximately 33% of the total mercury in the Afton smelter feed occurs as tennantite, 51% is present as a solid solution in native copper and 16% occurs as mercurian silver (amalgam). The mercurian silver is usually present as very fine-grained (1-2 μm) inclusions in native copper. Consequently, at least 67% of the total mercury in the feed will always follow native copper into the smelter. Arsenic in the smelter feed occurs mainly (approximately 100%) as tennantite and the contribution by pyrite is negligible.

Under current smelting conditions at the Afton smelter, approximately 99.6% of the total mercury in the feed enters the off-gas cleaning system and the off-gas to the mercury scrubber itself carries approximately 94% of the total mercury. Approximately 78% of the total arsenic in the smelter is retained in the copper product; 20% is carried by the dust and slag and is subsequently recirculated to the flotation circuit; 1.8% is discharged as sludge, and less than 0.2% enters the mercury scrubber.

ACKNOWLEDGEMENTS

The co-operation of Afton Mines Limited is greatly appreciated. The authors wish to thank Dr. J.E. Dutrizac for critical reading of this manuscript, D. Owens and L. Wilson of CANMET for technical assistance and W.J.S. Craigen (CANMET) and W.A. Lemmon (Environment Canada) for obtaining samples for this study.

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TABLE 1. MERCURY CONTENTS OF THE AFTON SMELTER FEED, DUSTS AND PRODUCTS

Sample	Hg (ppm) in dried solids*	Total Hg (ppm) in dried solids and scrubber	% Hg driven off during drying
(Samples collected on Dec. 2, 1980)			
Flot. conc. (dried at 180-200°C)	92	94	2.2
Flot. conc.	99	99	0
Metallic conc.	106	106	0
Native copper in metal. conc.	115	115	0
Slag	0.3	0.3	0
Copper product	0.4	0.4	0
ESP dust	69	69	0
Sludge** ($CaSO_4 . \frac{1}{2}H_2O$) #1	94	100	6.0
Sludge*** ($CaSO_4 . \frac{1}{2}H_2O$) #2	102	107	4.7
Samples collected on Feb. 16, 1981)			
Recycle dust/lime slurry**	158	158***	--
Recycle dust from dryer	67	67***	--
Venturi scrubber underflow (pH = 7)	0.4	0.4***	--

* Sample dried at 70°C under N_2, unless otherwise indicated.

** Hg found in supernatant is neglibible with respect to the Hg in the solids.

*** Hg in scrubber (formed by drying at 70°C) was not analyzed. The amount is assumed to be negligible with respect to the Hg in the solids.

TABLE 2. CHEMICAL ANALYSES OF THE AFTON SMELTER FEED, DUST AND PRODUCTS

Sample*	S	Cu	Pb	As	Fe	Ag	Zn	Sb
(Samples collected on Dec. 2, 1980)				Wt%				
Flot. conc. (dried at 180-200°C)	4.25	52.90	<0.01	0.31	3.87	0.017	0.06	-
Flot. conc.	4.03	52.63	<0.01	0.30	3.90	0.017	0.06	-
Metallic conc.	0.13	79.8	<0.01	0.03	11.0	0.015	0.01	0.01
Native copper in metal. conc.	0.06	97.81	-	-	-	0.025	-	-
Slag	0.06	4.04	0.02	0.08	14.26	<0.001	0.29	-
Copper product	0.01	96.12	<0.01	0.33	0.01	0.039	0.01	0.01
ESP dust	11.47	35.41	0.04	0.59	9.10	0.025	0.12	0.08
Sludge #1	17.34	<0.01	<0.01	0.11	<0.01	<0.001	<0.01	-
Sludge #2	17.52	<0.01	<0.01	0.10	<0.01	<0.001	<0.01	-
(Samples collected on Feb. 16, 1981)								
Recycle dust/lime slurry	8.47	18.30	0.06	1.61	1.09	0.02	0.10	-
Recycle dust from dryer	6.03	43.77	<0.01	0.33	4.69	0.02	0.05	-
Venturi scrubber underflow	21.3 g/l	2 ppm	1 ppm	0.01	0.4 ppm	0.1 ppm	0.1 ppm	-

* All samples were dried at 70°C under N_2, unless otherwise indicated.

TABLE 3. ELECTRON MICROPROBE ANALYSES OF NATIVE COPPER

	1*	2**	3	4	5	6	7
Ag	0.00	0.01	nd	nd	nd	0.1	0.1
Hg	0.01	0.01	0.08	0.10	0.09	0.34	0.11
Cu	99.64	99.65	99.8	99.9	99.6	99.7	99.9
Total	99.65	99.66	99.88	100.00	99.69	100.14	100.11

	8	9	10	11***	12	13	14
Ag	nd	0.1	nd	0.00	0.1	nd	nd
Hg	0.14	0.11	0.10	0.01	nd	nd	nd
Cu	99.8	100.2	99.7	99.65	98.6	95.7	94.9
As	nd	nd	nd	0.00	0.4	3.6	4.1
Total	99.94	100.41	99.80	99.66	99.1	99.3	99.0

Sb and As were not detected in No. 1-11

Minimum detection limit: Hg 0.08 wt%, Ag 0.08 wt%, As 0.06 wt%

* No. 1 Average of 24 grains from metallic concentrate

** No. 2 Average of 23 grains from flotation concentrate

*** No. 11 Average of 76 grains from metallic and flotation concentrates

No. 3-8 Native copper from metallic concentrate

No. 9-10 Native copper from flotation concentrate

No. 12-14 Arsenic-bearing native copper from metallic concentrate.

TABLE 4. ELECTRON MICROPROBE ANALYSES OF CHALCOPYRITE, BORNITE AND CHALCOCITE

	Chalcopyrite		
	Untarnished*	Tarnished**	Average***
Fe	30.35	29.40	30.06
S	34.96	33.74	34.20
Cu	35.00	36.65	36.27
Total	100.31	99.79	100.53

	Bornite†	Chalcocite††
Fe	10.94	-
S	24.97	19.57
Cu	63.02	80.90
Ag	nd	<0.01 (0.0-0.15)
Hg	nd	<0.01 (0.0-0.15)
As	nd	<0.01 (0.0-0.08)
Total	99.93	100.47

* Average of 23 untarnished grains from flotation conc.

** Average of 19 tarnished grains from flotation conc.

*** Average of 58 grains (tarnished and untarnished) from flot. conc.

† Average of 10 grains from flotation conc.

†† Average and ranges of 30 grains

Ag, Hg and As were not detected in chalcopyrite (minimum detection limits: Ag 0.06, Hg 0.09, As 0.07 wt%).

TABLE 5. ELECTRON MICROPROBE ANALYSES OF NATIVE GOLD AND AURICUPRIDE

	Native gold			Auricupride		
Ag	6.9	7.5	6.9	0.5	0.2	0.2
Au	91.5	89.4	90.0	50.4	50.5	50.7
Cu	2.4	3.2	2.2	49.1	49.2	49.0
Total	100.8	100.1	100.0	100.0	99.9	99.9

Hg was not detected. Native gold is intergrown with the auricupride from flotation concentrate.

TABLE 6. ELECTRON MICROPROBE ANALYSES OF MERCURIAN SILVER

	1*	2	3	4	5	6	7
Ag	83.96	97.2	87.2	86.9	90.9	91.1	78.3
Cu	3.09	-	3.0	2.7	0.1	0.3	6.6
Hg	8.19	4.6	9.1	9.3	9.0	8.7	16.3
Total	100.24	101.8	99.3	98.9	100.0	100.1	101.2

	8	9	10	11	12	13	14
Ag	74.9	79.7	95.2	98.8	90.1	91.9	89.8
Cu	7.8	4.5	3.2	1.2	4.2	8.2	0.5
Hg	17.4	14.9	1.9	0.3	5.8	0.7	8.2
Total	100.1	99.1	100.3	100.3	100.1	100.8	98.5

Gold and Sb were not detected.

No. 2-6 from flotation concentrate

No. 7-14 from metallic concentrate

Mercurian silver occurs as inclusions in native copper, except

No. 7-9 where mercurian silver occurs as intergrowths with native copper

*Average of 16 grains

TABLE 7. ELECTRON MICROPROBE ANALYSES OF CUPRITE AND DELAFOSSITE

	Cuprite			Delafossite	
	1	2	3	4	5
TiO_2	0.1	0.1	0.2	1.6	1.4
FeO	0.8	1.1	3.9	44.0	43.9
Cu_2O	99.2	98.4	97.6	-	-
CuO	-	-	-	54.3	54.2
Total	100.1	99.6	101.7	99.9	99.5

TABLE 8. ELECTRON MICROPROBE ANALYSES OF PYRITE

	1 *	2 **	3	4	5
Fe	45.16	45.36	45.9	46.2	45.0
Cu	1.40	1.20	1.1	0.8	2.4
As	0.36	0.32	0.3	-	-
S	52.60	52.57	52.6	52.9	52.9
Total	99.52	99.45	99.9	99.9	100.3

	6	7	8	9	Range*
Fe	42.8	42.9	45.1	45.7	42.2 - 46.6
Cu	-	-	1.5	1.5	0.6 - 2.4
As	4.3	2.3	0.3	-	0.0 - 4.3
S	42.8	54.1	52.8	53.3	52.3 - 54.1
Total	99.9	99.3	99.7	100.5	99.3 -101.2

* Average or ranges of 152 grains from flotation concentrate.

** Average of 41 freshly polished grains (sample analyzed within 15 minutes after polishing). Minimum detection limit: As 0.07 wt%.

TABLE 9. ELECTRON MICROPROBE ANALYSES OF TENNANTITE

	1	2	3	4	5	6	7	8
Ag	nd	nd	nd	nd	.1	nd	.1	.2
Cu	45.6	42.7	41.3	48.8	43.2	44.9	40.6	48.0
Fe	1.7	0.7	2.3	2.1	.5	6.7	1.5	2.1
Zn	4.6	5.4	4.5	2.2	5.8	.2	5.0	1.5
Hg	nd	.85	.75	.11	1.21	.11	.23	.61
Sb	0.3	10.3	14.4	.3	10.7	1.5	18.1	4.3
As	19.8	12.5	10.3	18.8	12.7	18.9	7.5	16.3
S	29.0	27.1	27.2	27.1	27.2	28.7	26.5	28.1
Total	101.0	99.5	100.75	99.41	101.41	101.01	99.53	101.11

	9	10	11	12	13	14	Av.*	Range*
Ag	nd	nd	nd	.2	nd	nd	0.00	0.0 - 0.2
Cu	48.5	44.0	42.1	44.2	44.4	43.0	44.46	40.6 - 48.8
Fe	3.8	2.2	.1	1.5	4.0	.5	3.32	0.1 - 6.7
Zn	.5	4.2	7.2	4.2	3.3	6.1	3.11	0.2 - 6.1
Hg	.10	1.82	.71	.74	nd	.22	.23	0.0 - 1.8
Sb	.4	2.0	4.4	11.4	2.9	13.2	4.72	0.3 - 18.1
As	19.3	18.3	16.4	11.6	17.9	10.9	16.67	7.5 - 19.8
S	28.2	28.0	28.3	27.6	28.9	26.8	28.02	26.5 - 29.0
Total	100.8	100.52	99.21	101.44	101.42	100.72	100.53	99.2 - 101.5

* Average or ranges of 92 grains from flotation concentrate. Minimum detection limits: Hg 0.10 wt%, Ag 0.08 wt%.

Anal. No. 10 corresponding to $(Cu_{10.31}Fe_{0.59}Zn_{0.96}Hg_{0.14})_{\Sigma 12.00}(As_{3.64}Sb_{0.24})_{\Sigma 3.88}S_{13}$.

Av. anal. corresponding to $(Cu_{10.42}Fe_{0.88}An_{0.71}Hg_{0.02})_{\Sigma 12.03}(As_{3.31}Sb_{0.58})_{\Sigma 3.89}S_{13}$.

TABLE 10. ELECTRON MICROPROBE ANALYSES OF WHITE SUBSPHERICAL AGGREGATES* IN DRYER DISCHARGE

	1	2
CaO	20.9	13.7
MgO	18.9	20.6
SO_3	0.4	0.4
SiO_2	0.7	7.1
Total	40.9	41.8

No. 1 clean, white particles, stable in vacuum conditions.

No. 2 dark, stained particles, unstable in vacuum conditions.

* Possibly dust particles of burnt lime: X-ray diffraction analyses showed the presence of $CaCO_3$, $Ca(OH)_2$ and $Mg(OH)_2$.

TABLE 11. ELECTRON MICROPROBE ANALYSES OF METALLIC COPPER IN THE COPPER PRODUCT

	1	2	3	4	5	6
Cu	99.5	100.4	99.1	98.6	99.3	99.3
Ag	.08	0.0	.08	.06	.04	.04
As	.44	.06	.81	.68	nd	.48
Hg	-	-	-	-	.16	.13
Sb	-	-	-	-	.07	.11
Total	100.02	100.46	99.99	99.34	99.57	100.06

	7	8	9	10	Av*	Range*
Cu	99.0	99.1	99.31	99.8	99.31	98.6-100.0
Ag	.08	.06	.04	nd	.035	0.0-0.08
As	.53	.69	.81	.52	.265	0.0-0.81
Hg	-	-	nd	nd	.00	0.0-0.16
Sb	-	-	.26	nd	.06	0.0-0.26
Total	99.61	99.85	100.42	100.32	99.67	99.3-100.6

*Average or ranges of 68 grains.

Minimum detection limits: Ag 0.03 wt%, As 0.06 wt%, Hg 0.09 wt%, Sb 0.07 wt%.

TABLE 12. ELECTRON MICROPROBE ANALYSES OF THE Cu-Sb-As-O PHASE FOUND IN THE COPPER PRODUCT

	1	2	Av.*
Cu_2O	55.3	53.4	54.4
Sb_2O_3	16.9	16.9	16.9
As_2O_3	27.5	30.0	28.8
Total	99.7	100.3	100.1

* Corresponding to $Cu_{13.08}As_{5.01}Sb_{1.99}O_{17.04}$

TABLE 13. ELECTRON MICROPROBE ANALYSES OF SOME ARSENIC-BEARING SPHERULES IN ELECTROSTATIC PRECIPITATOR DUST

	Cu_2O+CuO*	$CaSO_4$*	$CaSO_4$	Cu_2O-As_2O_5	"As_2O_5"	Glass	Cu_2O-As_2O_5-$SO_4^=$
Cu_2O**	98.4	-	-	89.7	-	-	78.1
CuO**	-	1.7	0.9	-	1.1	27.3	-
As_2O_3**	0.7	-	-	-	-	-	-
As_2O_5**	-	1.0	2.2	8.2	82.5	41.1	5.6
SO_3	-	58.7	58.9	1.6	8.1	2.9	15.1
K_2O	-	-	0.1	-	0.2	5.3	0.8
CaO	-	39.1	38.6	-	0.3	12.9	0.3
SiO_2	-	-	-	-	0.6	7.9	0.6
Total	99.1	100.5	100.7	99.5	93.1	97.4	100.5

*Average composition of 30 spherules.

**Oxide forms are arbitrarily assigned.

TABLE 14

MERCURY BALANCE FOR THE AFTON SMELTER

	Stream	Approx. Hg Concentration (ppm)	Weight (kg/y)	Distribution %
INPUT * TO TBRC	- Flotation concentrate	97	3299	78
	- Metallic concentrate	106	930	22
				100
RECYCLE	- TBRC ESP Dust	69	42	1
	- TBRC Slag to Mill	0.3	8	<<1
	- Dust from Dryer	67	N/A	est. <1
OUTPUTS	- Copper Product	0.4	8	<<1
	- SO_2 Scrubber Sludge	104	195	5
	- Off-gas to Hg Scrubber	-	3975	94

* Inputs to TBRC = 100. The flotation concentrate stream contains mercury from the ore, the dryer dust-lime slurry, the TBRC dust and possibly a small amount from the slag. The metallic concentrate stream contains mercury from the ore and possibly a minute amount from the recycled slag.

TABLE 15

ARSENIC BALANCE FOR THE AFTON SMELTER

		Approx. As Concentration (%)	Weight (kg/y)	Distribution %
INPUT * TO TBRC	- Flotation Concentrate	0.30	99207	97
	- Metallic Concentrate	0.03	3068	3
				100
RECYCLE *	- TBRC ESP dust	0.59	4091	4
	- TBRC Slag to Mill	0.08	16364	16
	- Dust from Dryer	0.33	N/A	est. < 1
OUTPUTS	- Copper Product	0.33	79775	78
	- SO_2 Scrubber Sludge	0.10	1841	1.8
	- Off-gas to Hg Scrubber	-	205	0.2

* Inputs to TBRC = 100. The flotation concentrate stream contains arsenic from the sulphide concentrate, dryer dust-lime slurry, the TBRC electrostatic precipitator recycle dust and possibly some from the slag recycle. The metallic concentrate stream contains arsenic from the ore and the recylced slag.

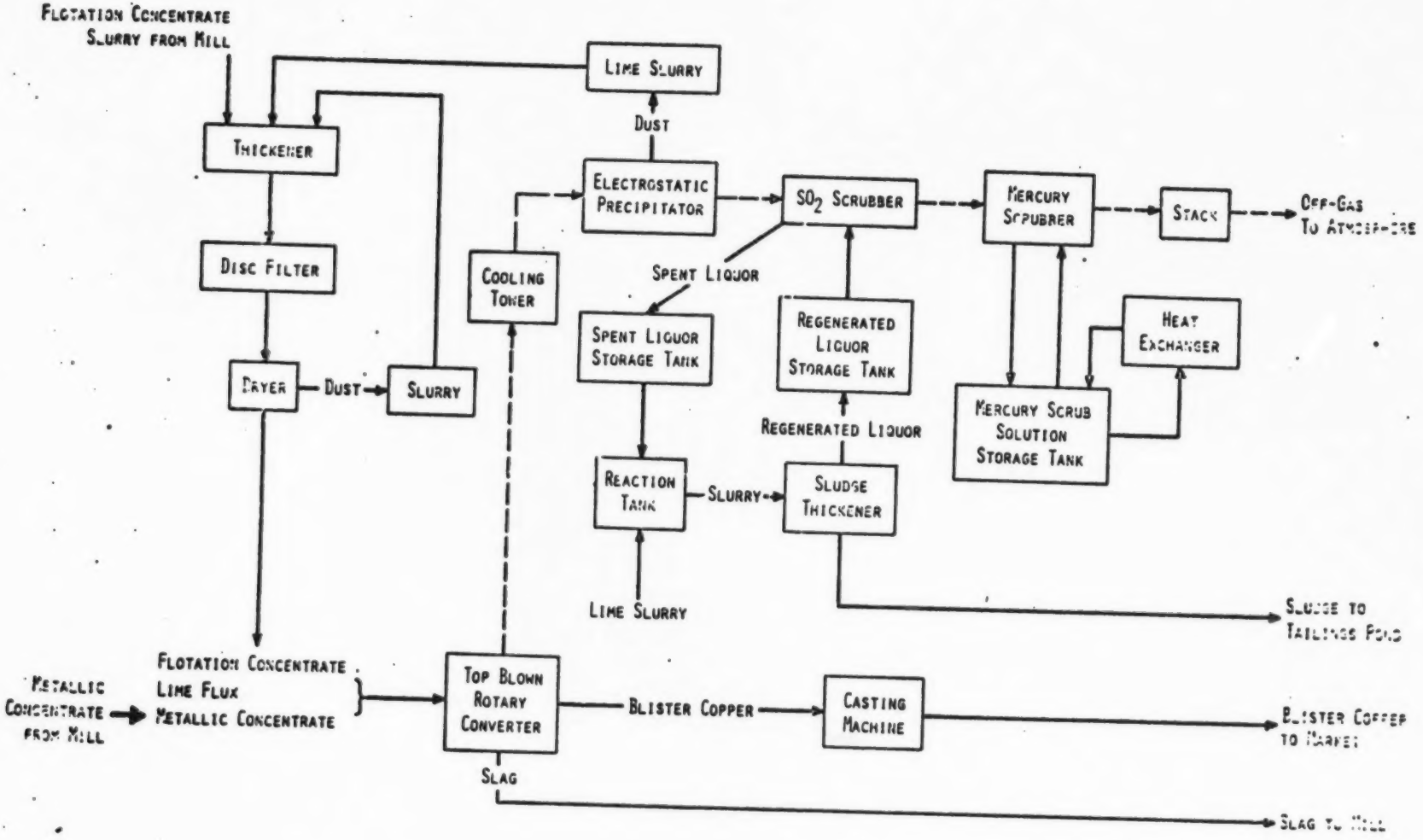

Fig. 1 Afton Smelter flowsheet

Fig. 2 SEM backscattered electron (BSE) image of flotation concentrate (dryer discharge) showing major minerals of native copper (a), chalcocite (b) and gangue minerals (c).

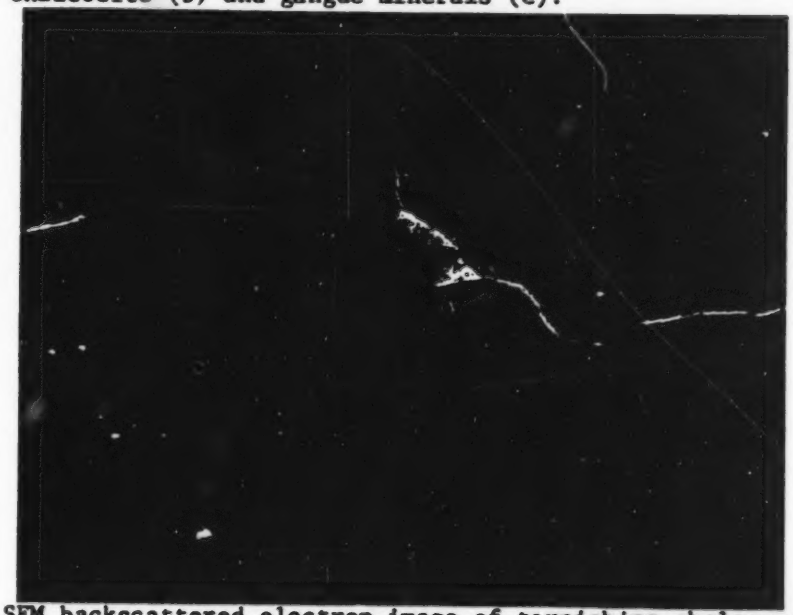

Fig. 3 SEM backscattered electron image of tarnishing chalcopyrite, showing chalcopyrite as host phase and bornite as exsolution lamellae. The inclusion in the center is bornite.

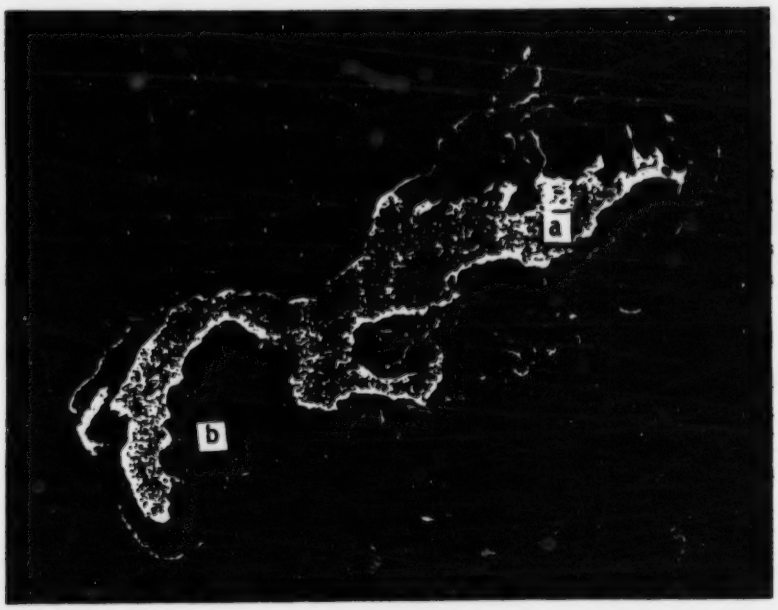

Fig. 4 BSE image showing intergrowth of native gold (a) and auricupride (b).

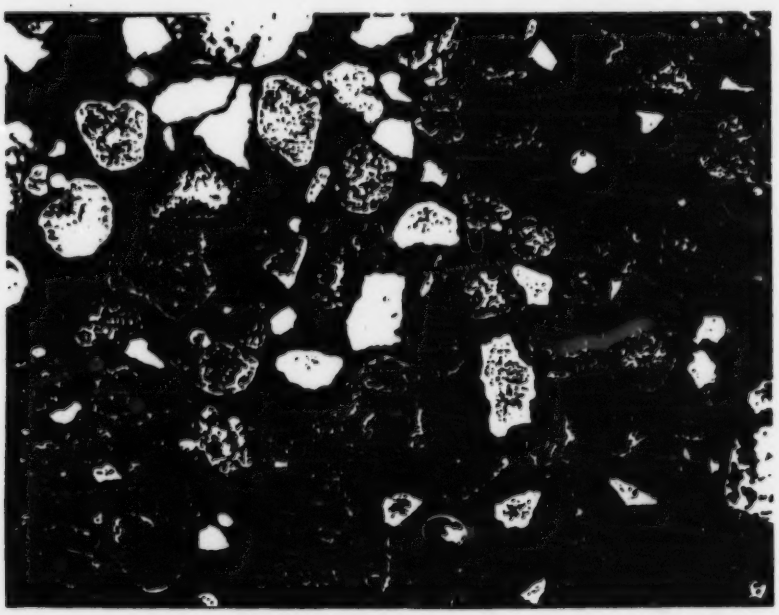

Fig. 5 BSE image of subspherical aggregates (grey) of $CaCO_3$, $Mg(OH)_2$ and $Ca(OH)_2$. The aggregates are possibly burnt-lime dust.

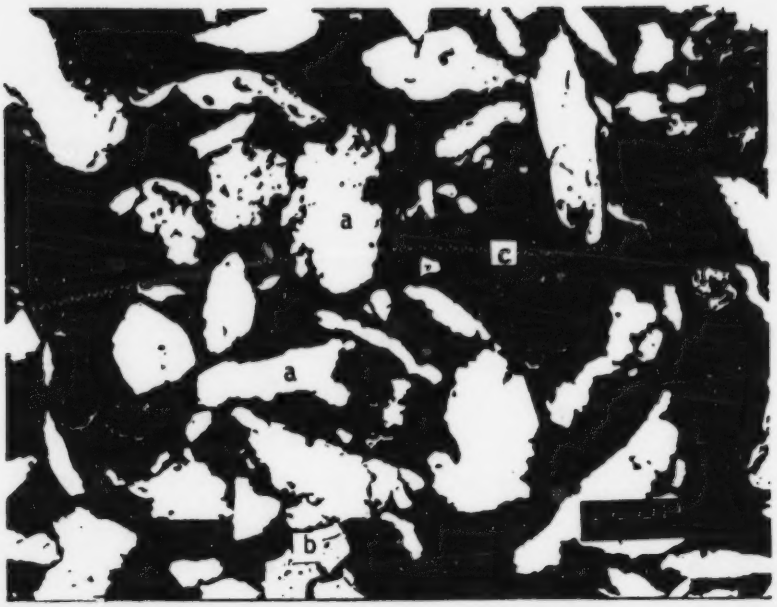

Fig. 6 BSE image of metallic concentrate, showing major minerals of native copper (a), magnetite-hematite intergrowth (b) and gangue minerals (c).

Fig. 7 BSE image of intergrowth of mercurian silver (a) and native copper (b).

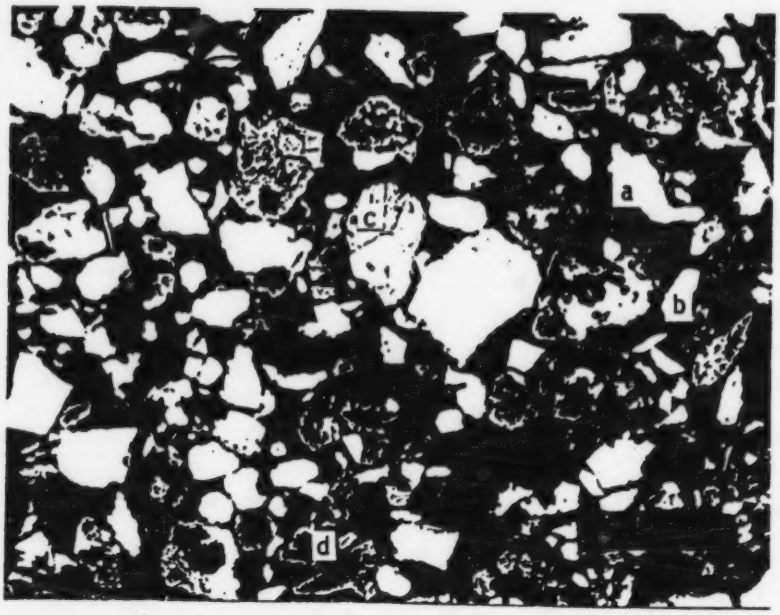

Fig. 8 BSE image of recycle dust from dryer, showing major constituents of native copper (a), chalcocite (b), hematite (c) and silicate minerals (d).

Fig. 9 BSE image of the copper product. The subspherical inclusions (grey) are Cu_2O.

Fig. 10 BSE image of the copper product showing inclusions of Cu_2O (subspherical) and $Cu_{13}Sb_2As_5O_{17}$ (stringers).

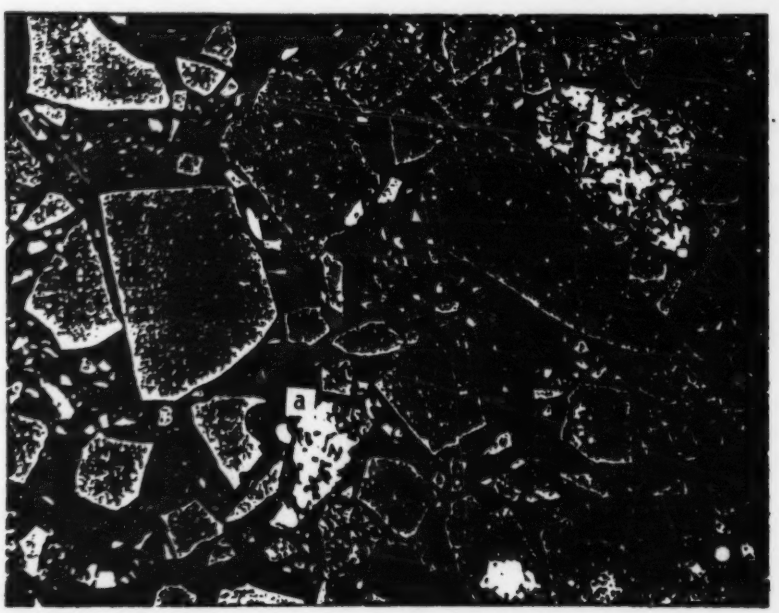

Fig. 11 BSE image of slag, showing spherical metallic copper (bright) and euhedral Fe-Cr spinel (a) in matrix (dark grey) of pyroxene and glass.

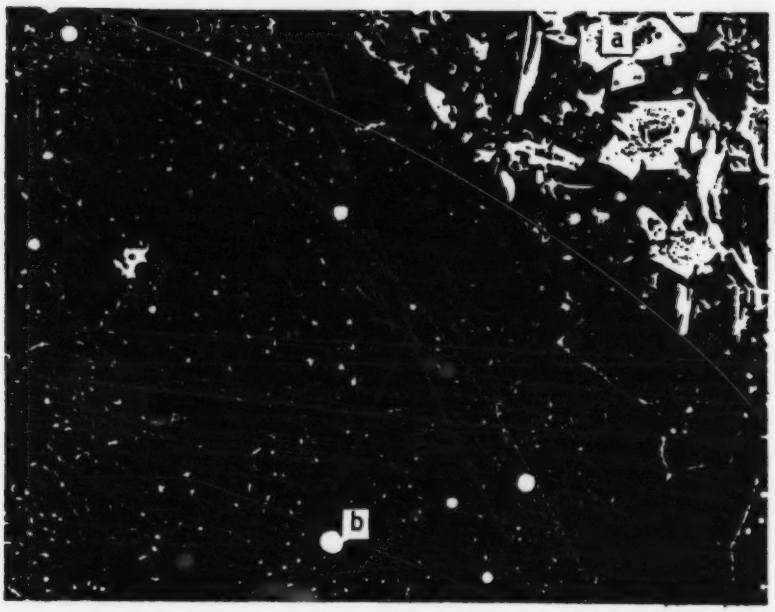

Fig. 12 BSE image of slag, showing the detail of the two large grains in the upper right corner of Fig. 11. The euhedral crystals are Fe-Cr spinel (a), the dendrites are pyroxene, the spherules are metallic copper (b), the matrix is silicates and possibly glass.

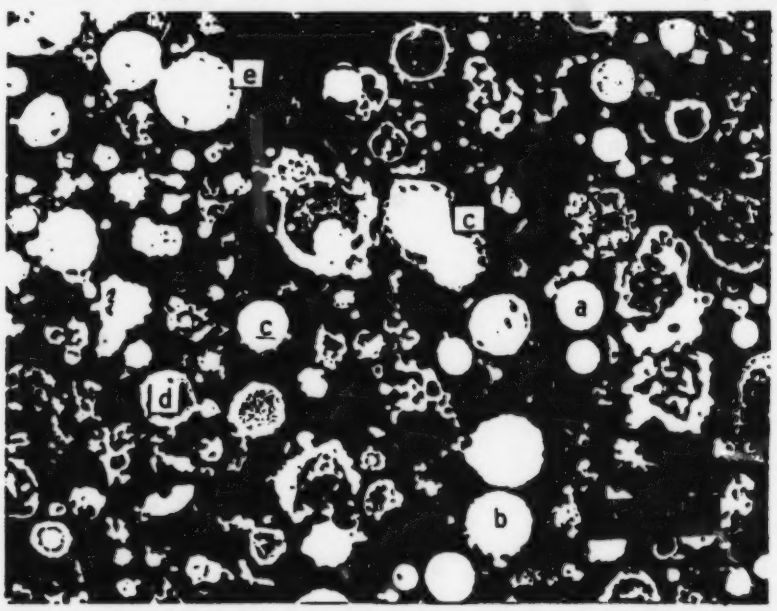

Fig. 13 BSE image of electrostatic precipitator dust showing spherules of metallic copper (a), Cu_2O-CuO (b), $CuSO_4$ or $CuSO_4$. $5H_2O$ (c) and glass (d). The irregular aggregates are Cu-Fe oxide, glass and Cu sulphates. Metallic copper spherules and Cu_2O-CuO spherules usually have rims of $CuSO_4$, $CuSO_4.5H_2O$ or $(Ca,Cu)SO_4$ (e).

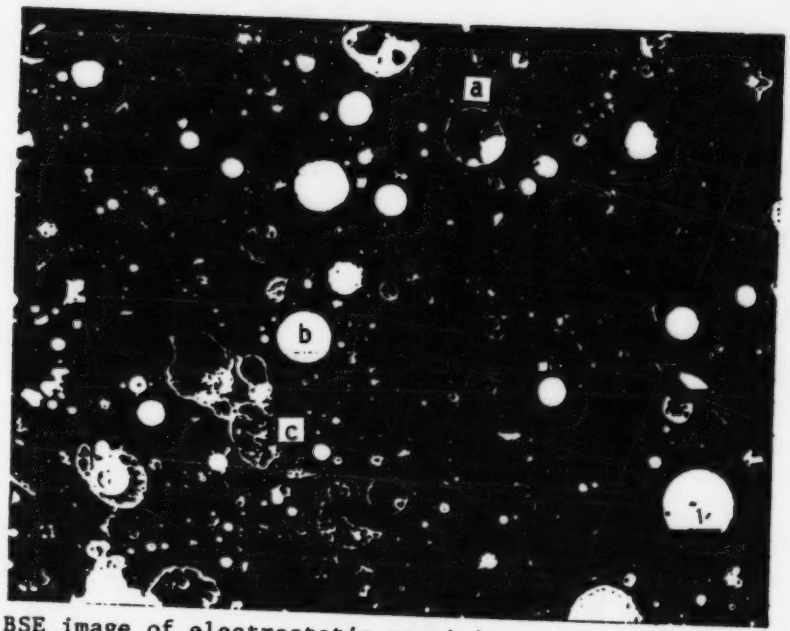

Fig. 14 BSE image of electrostatic precipitator dust showing the heterogeneity of the compositions of glass spherules (a); the variations of brightness in the spherules indicate the variations of composition within the spherule. The bright colored spherules (b) are intergrowths of Cu_2O and CuO, the irregular grains (c) are glass, Cu-Ca sulphates and arsenates. Some of the grey spherules are As-carriers. The rims (light grey) of Cu_2O-CuO spherules are usually $CuSO_4$ or $CuSO_4.5H_2O$.

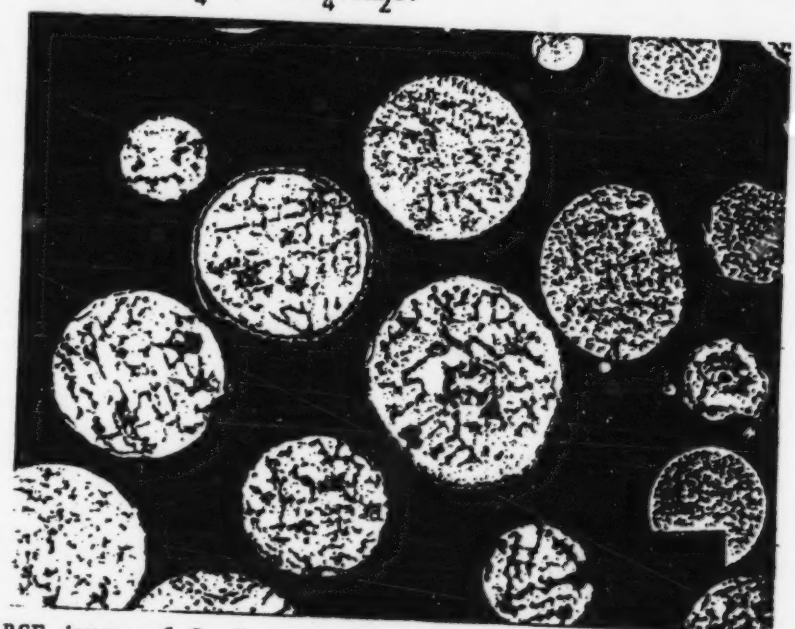

Fig. 15 BSE image of Cu_2O-CuO spherules. The minor phase (grey) is CuO, the major phase (light grey) is Cu_2O, and the bright colored inclusions are metallic copper. The rims of the spherules are $CuSO_4$ and $CuSO_4.5H_2O$.

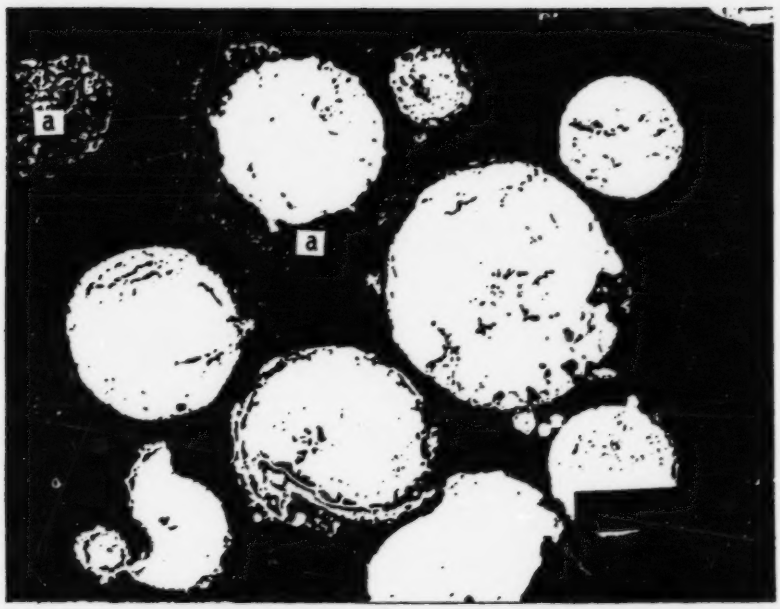

Fig. 16 BSE image of Cu_2O-CuO spherules. In the spherules, the light grey phase is Cu_2O, the grey phase is CuO, the bright colored inclusion is metallic copper. The rims of the spherules are $CuSO_4$ or $CuSO_4 \cdot 5H_2O$. The dark grey spherules or rims are $(Ca,Cu)SO_4$ (a).

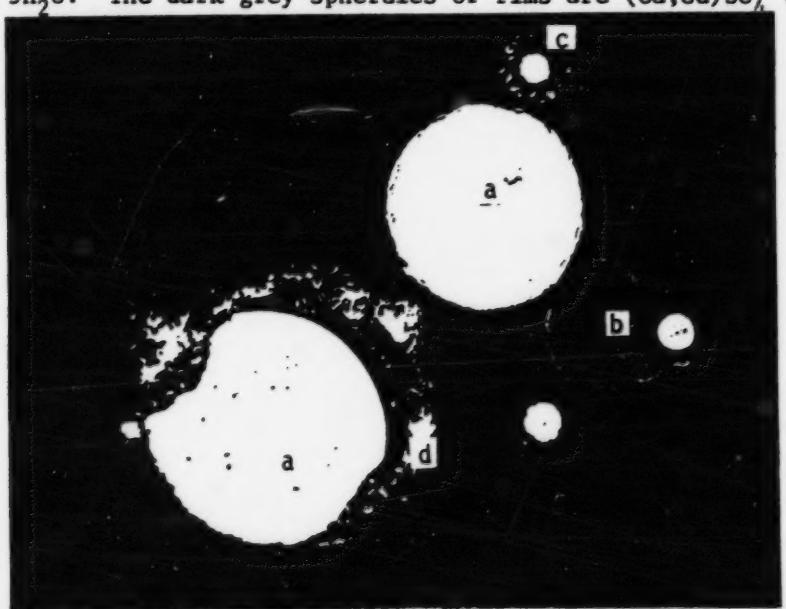

Fig. 17 BSE image of Cu_2O-CuO (a) and $CuSO_4$ (b) spherules. The broad greyish rim (c) on the small Cu_2O-CuO spherule is Cu-(K)-$SO_4^=$-H_2O; the inner rim on the largest Cu_2O-CuO spherule is Cu-(Ca)-$SO_4^=$, the outer rim is CaO-CuO-MgO-Al_2O_3-K_2O-SiO-$SO_4^=$, and the bright grain (d) is metallic copper.

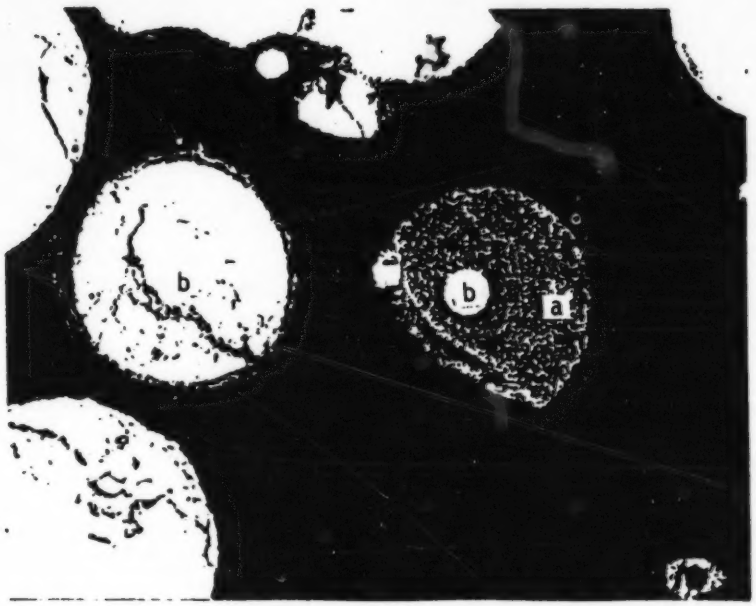

Fig. 18 BSE image of $CuO-As_2O_5-K_2O-CaO-SiO_2-SO_4^{=}$ spherule (a) (Table 13); The other spherules are Cu_2O-CuO (b).

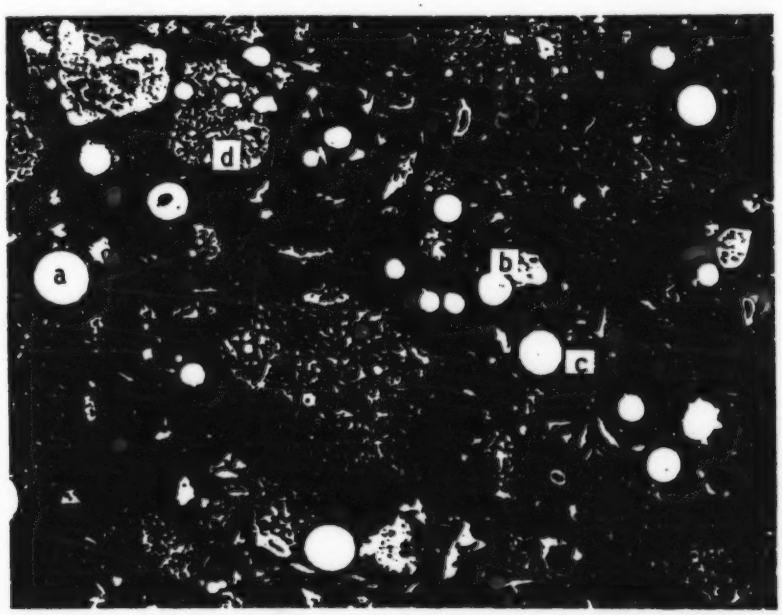

Fig. 19 BSE image of dried solids of recycle dust-lime slurry showing Cu_2O-CuO (a), glass (b) and Cu-Ca sulphate spherules (c). The irregular grains and the fine-grained particles (d) are mostly $(Ca,Cu)SO_4$ and $CaSO_4$.

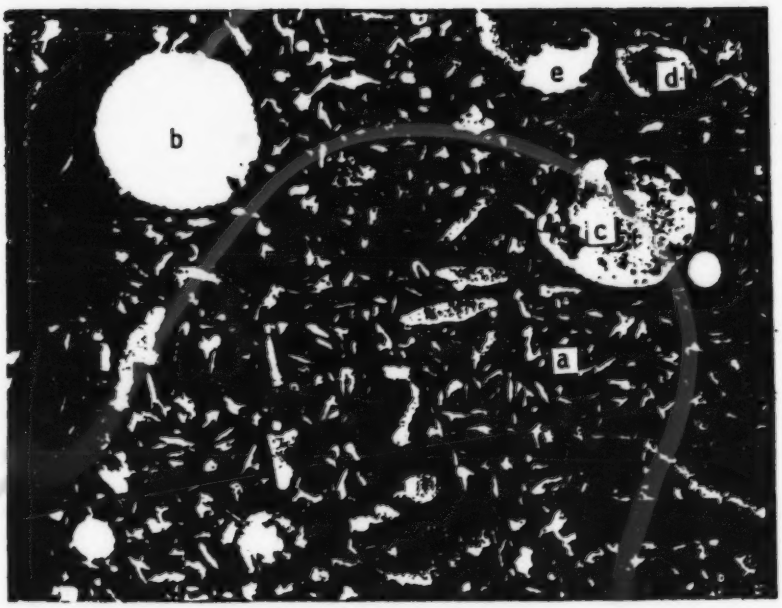

Fig. 20 BSE image of dried solids of recycle dust-lime slurry, showing the detail of the fine-grained particles (a) of $(Ca,Cu)SO_4$ and $CaSO_4$, (b) Cu_2O-CuO, (c) $CuSO_4$, (d) glass, (e) metallic copper. Enlargement of area d in Fig. 19.

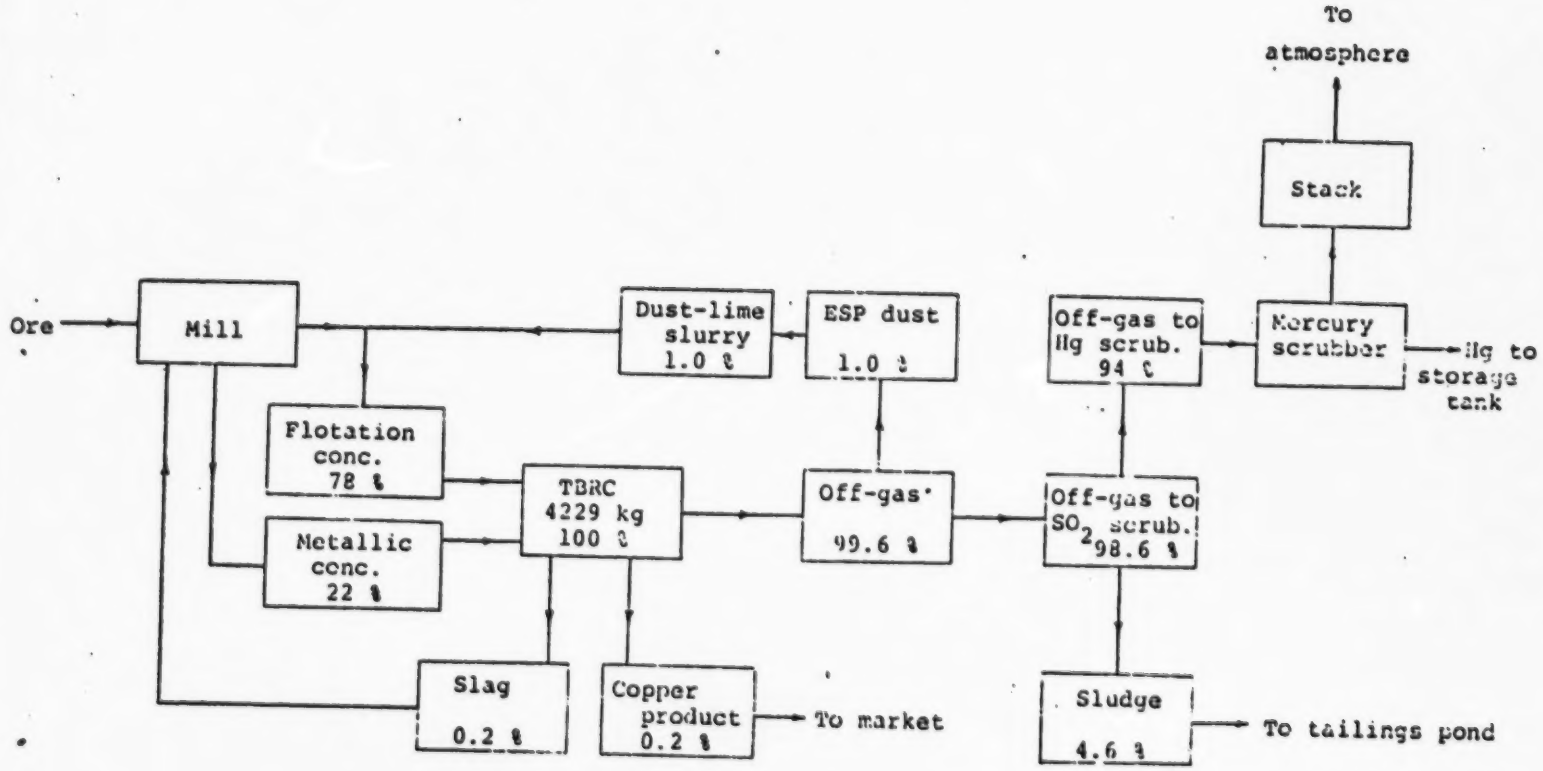

Fig. 21. Distribution of mercury in the Afton smelter.

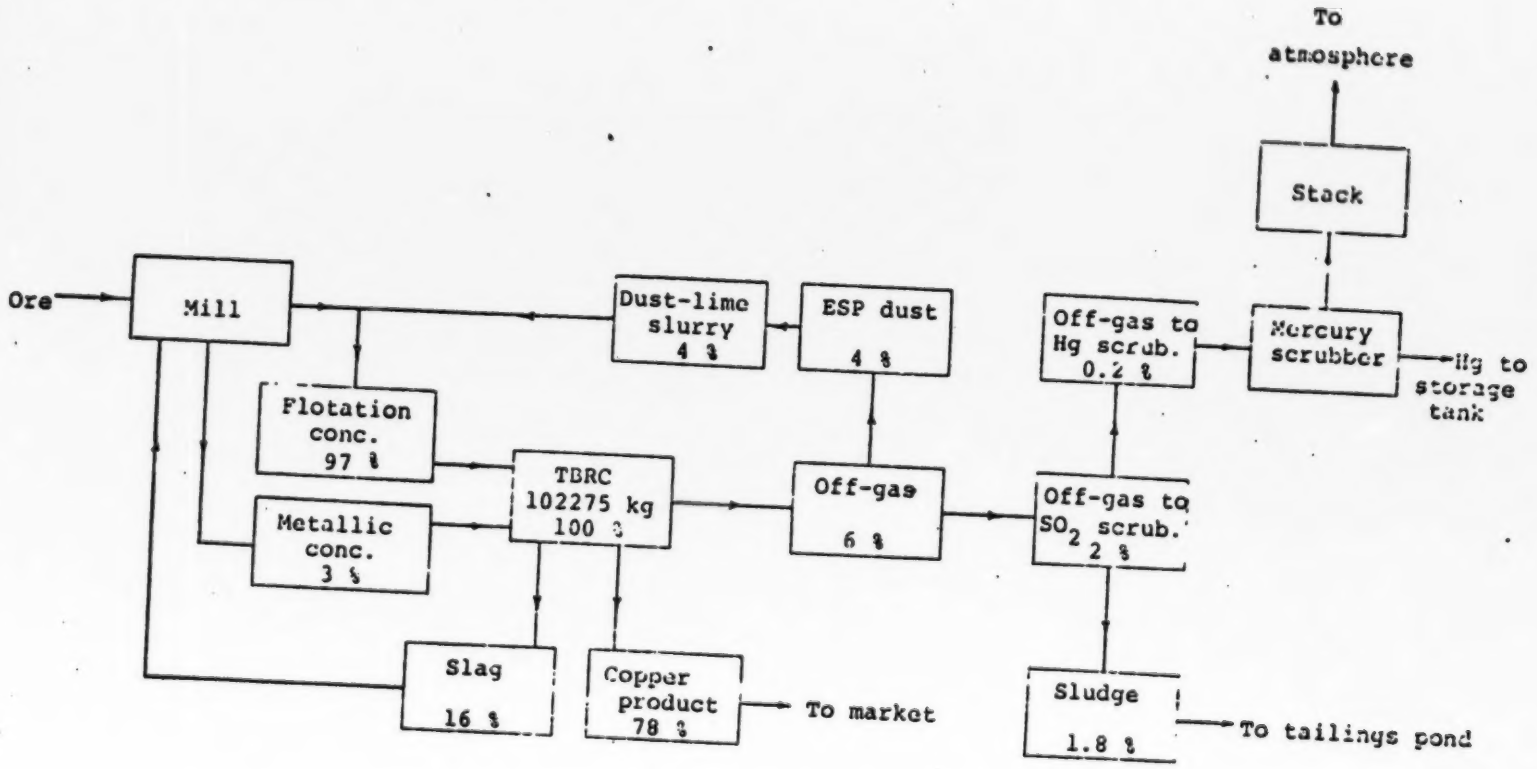

Fig. 22. Distribution of arsenic in the Afton smelter.